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Sustainable co-generation from the tides: A review

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1. What is tidal energy?

Standing on the shores near St Malo (France), on the Bay of Fundy (Canada), or Broome (Australia), one is deeply impressed by the forceful landwards rush of the "wall" of water that heightens sea-level by as many as 15 m (50 ft). The energy dissipated by the tide that rolls in fires modern man's imagination as he dreams about the amount of electricity that could be generated if this energy could only be captured. Forest de Bélidor had, already more than two centuries ago, expressed similar thoughts in his lectures at the French Military School. Realistically, of course, only a relatively small amount of this energy could ever be transformed into "power".

2. The tides

2.1. Tide Generation

The tide-generating forces encompass the gravitational pull of principally sun and moon and the rotational force of the earth. The difference in tide occurrence is caused by the *tidal day* being 1.035 times as long as the *solar day*. Superimposed are the earth's revolution and the moon's declination. The tidal effects caused by other celestial bodies are all but negligible, due to their distance from the earth. These forces create high tides on the sides of the earth nearest to and farthest from the moon, separated by a low tide belt.

Most tides occur twice a day (two highs, two lows) but in some geographical areas there is only one tide a day. The periodicity of other types of tides may be far less, for instance that of equinoctial and spring tides, or even exceptional such as those occurring less than once a century (e.g. March 27, 1967 in The English Channel).

The gravitational attraction exerted by the moon upon the earth and an inertial effect are the primary causes of the tides. They rise and fall twice a day as the earth rotates upon itself. The moon also rotates but slightly out of phase with the solar day, thus semidiurnal tides are spaced 12 hours and 25 minutes apart. The sun's gravitational pull has a lesser effect—approximately 2 1/4 times—, and so does that of other planets. The changing angles of moon and sun vis-à-vis the earth cause a diurnal tide that superimposes itself on the semidiurnal pattern.

There are still other tides, less frequent, such as spring and neap tides, due to the alignment of earth, moon and sun, or tropical, equinoctial, mammoth tides. Unequal range tides occur with two highs and two lows in the course of a lunar day. Depth, shape, size of a basin modify the type of tide and in some areas the semidiurnal tides are of approximately equal amplitude.

Diurnal tides have only one high and one low per lunar day; their period is double that of the semidiurnal tides.

Tidal energy harnessing is aimed at semidiurnal and diurnal tides. The tidal energy is derived from the earth's inherent force, to wit the earth's rotation within the disturbing field of sun and moon compares to the movement of an alternator's rotor in

the field of a stator. The tidal wave is disturbed by land masses, narrow passages and shallows. The tidal current is the rotary current accompanying the tide crest in the open ocean and becomes a reversing current, near shore, that moves in and out, as flood and ebb currents. Both the rise and fall movement, and the flood and ebb, can be transformed into mechanical and electrical energy.

2.2. Tidal power resource

Theoretically the rise and fall of tides dissipates 3000 million kilowatts of which one billion in shallow seas. A major requirement to harness tidal power used to be a rather high usable head in a site favorable for engineering work and near a reasonably promising market. That eliminated four fifths of the theoretically available energy. This credo dominated thinking 20, even ten years ago.

Subsequent developments in low-head turbines technology dramatically altered the situation, making hundreds of new sites “suitable”. But thinking changed also in regards size of plants. Thus gigantic schemes such as that of the Chausey Islands (French Atlantic coast) were shelved and small centrals came upon the scene. China has elected to go that route and reputedly built more than 100 plants, further reducing capital investment (a frequent stumbling block for proposed schemes) by utilizing existing dams rather than building new barrages [1]. Eliminating cofferdams in the construction process and bringing to the site cells or units assembled on land represents a further economy; this approach was selected by the Soviets when building their small plant on Kisgalubskaia Bay (near Murmansk, Russian Federation).

Electricity production does not always coincide with consumption demand. Indeed, tides are linked to the lunar rather than the solar cycle. To remedy this situation various systems of “re-timing” have been proposed. This can be achieved by adding to the plant (but also to its capital cost) storage basin[s], or by judiciously choosing opening and closing times of tide gates, thereby synchronizing power generation with peak-demand.

At the risk of pedantry one may talk of Kafkaesque situations: the rentability of a station is governed at least for a sizeable part, by the size of the [retaining] basin; lower production costs can be attained with larger basins and large tidal amplitudes. Large basins require long dams, thus a larger capital investment. Though by doubling the dam’s length basin size is quadrupled.

Gibrat [2] the “father” of France’s Rance River tidal power plant, devised a mathematical site value based on dam length (L) and natural energy; the natural energy (NE) being the annual theoretical production—expressed in kilowatt-hours—of unit turbines operating in both directions. The formula, obviously based on the use of bi-directional bulb turbines, provides a k value which the smaller it is indicates a better suited site:

$$k = L/NE$$

The geometric shape of the basin and its surface will of course determine the complexity of barrage building [3]; the ratio of the aperture section to the basin’s surface is important, to wit, its dimension in absolute value, basin minimum depth,

basin opening and more or less widening shape. In short there are oceanographic, geographic, geologic, technologic and economic factors at play.

The potential energy of tidal movement, for a tidal cycle of 6.2 h, can be estimated approximately by

$$E = \frac{A'\mathrm{m}\ \mathrm{g}\int_0^H \mathrm{h}\ \mathrm{dh}}{T} = \frac{\frac{1}{2}\times(103\ .\ 10^3)\ .\ H^2\ .\ (A\ .\ 10^6)}{60\ .\ 60\ .\ 62} = 225\ AH'\ (kw)$$

with

- A'=surface area of basin (m^2)
- A=surface area of basin (km^2)
- H=tidal range (m)
- h=head (m)
- g=gravity/acceleration (m^2/s)
- m=mass of seawater
- T=tidal period (inm)

Potential energy of tidal power sites has been calculated by Bernshtein (1961) [58], Gibrat (1966) [59] and Mosonyi (1963) [60] leading to the mathematical expression

$$E_\mathrm{p} = K\ .\ 10^6 AR^2$$

in which the coefficient K is the only to vary (1.92 and 1.97). R is either the average range (in meters) or the average range of the equinoctial tide, A is the basin area (in km^2), and E_p the potential energy (in kW/h/year). A type of utilization factor is introduced which is based on the system selected: for a single or double basin plant and a single tide it is 0.224, double tide 0.34 but 0.21 for a double basin; for a double basin, single tide with reverse pumping it is 0.277 and with pumps 0.234.

Tides and tidal currents must be differentiated, and their relation is not the same at all sites: the first are the vertical movement of the sea level (rise and fall), the second means the horizontal flow, sometimes called “run”. Tidal current power has, apart from Iceland, also been harnessed in the Faroë Islands. Information on plant and years of operation proved to be impossible to obtain. Even Icelandic specialists were unable to provide specifics at a US-embassy sponsored conference in 1972.

The current experienced at any given time is usually a combination of tidal and non-tidal currents. The tidal current in the unimpeded open ocean is normally rotary, clockwise in the northern, and counter-clockwise in the southern, hemisphere. Speed varies, with two maxima and two minima. It is reversing where flow—p.ex. straits or rivers—is restricted. The movement away from shore (downstream) is the ebb, and toward shore (upstream) is the flood. The maximum speed is attained at high and low tide, with directions being opposite to one another; it is nil when the direction inversion occurs.

Simple theory fails to accurately describe the tidal phenomenon because the earth is not uniformly covered by water, water depth varies, the Coriolis deflection plays a role, and so do geometrical shapes of basin and coast, and basin- or bay-size.

2.3. Power generation

To visualize the possibility of harnessing tides' energy the following formula provides the incremental amount of energy per cycle obtainable from the water displacement

$$\partial E = gR \ (DS \ \partial R)$$

integration gives

$$E = DgS \ . \ R^2/2$$

and with "double effect operation" the formula becomes

$$E_{\mathrm{max}} = Dg \ . \ R^2 S$$

wherein R is the tidal range, D water density, g acceleration due to gravity, S the area of the enclosed basin.

However only about 30% can in fact be retrieved, hence for a basin of one square kilometer, the capacity in kWh capable of handling the largest tides is

$$N_i = 311 \ AR^2$$

The maximum discharge through the barrage, in m^3/sec, is

$$Q_{\mathrm{max}} = 57 \ AR$$

The power formula applicable for emptying, filling and pumping is provided by the Gibrat-Lewis-Wickert equation

$$E_{\mathrm{e}} = \int_{z=0}^{H} \gamma f(z) z \partial z$$

Wherein respectively V_{b} V_{p} are the capacity (basin volume) and volume pumped, E_{c} E_{e} E_{f} E_{p} are, respectively, the *work* needed for a complete tidal cycle, to empty the basin, fill the basin, to pump

- $+A$, $-A$ are normal high water level and normal low water level
- $+C$ is a point above normal high water
- H is the tide height
- B is a water level
- $f(z)$ is the area of the basin as a function of water depth
- γ is the unit weight of water

To fill the basin it requires

$$E_f = \int_{z=0}^{H} \gamma f(z)(H-z)dz$$

A complete tidal cycle is $E_c = E_e + E_f$, thus

$$E_c = \int_{z=0}^{H} \gamma f(z)dz + \int_{z=0}^{H} \gamma f(z)(H-z)dz = \gamma^H \int_{z=0}^{H} f(z)dz$$

With basin volume

$$V_b = \int_{z=0}^{H} f(z)dz \rightarrow E_c = \gamma H B_b$$

The total volume changeover is $0 \rightarrow V_b$ to $0 \rightarrow 2V_b$ and consequently the mean operating head is $\frac{H}{2}$. The energy needed to lower level to level B, by pumping is

$$E_{p_1} = \int_{z=0}^{-B} \gamma f(z) z dz$$

- Flood tide provided energy is

$$E_{f_1} = \int_{z=-B} \gamma f(z)(H-z)dz$$

Energy needed to raise retaining basin level to level C+ is

$$E_{p_2} = \int_{z=H}^{+C} \gamma f(z)(z-H)dz$$

- Ebb tide provided energy is

$$E_{e_1} = \int_{z=0}^{H} -\gamma f(z)(z-H)dz$$

Thus net energy production for a complete tidal cycle is

$$E_e = E_{f_1} + E_{e_1} - (E_{p_1} + E_{p_2}) = H\int_{z=-B}^{C} f(z)dz = \gamma H(V_b + V_{p_1} + V_{p_2})$$

Difference between pumping and not pumping

$$E_{gain} = E_{c_4} - E_{c_3} = \gamma H(V_b + V_{p_1} + V_{p_2}) - V_b = \gamma H(V_{p_1} + V_{p_2})$$

E_c and E_{gain} are independent of basin shape and tide symmetry. Each basin has its proper natural frequency, depending on size and proportions, thus it is possible to take advantage of resonance and increase the tidal range during one cycle. With L length and d depth, the frequency is

$$T = \frac{2L}{\sqrt{gd}}.$$

Charlier [4] provided the calculation to find the net energy production for a complete cycle

$$E_c = H\int_{z=-B}^{c}$$

and the difference between operation of the plant involving or not involving pumping is $E_{gain} = \gamma H(V_{p_i} + V_{p_2})$.

3. A glimpse at history

Awe, fascination, amazement at the amplitude, scientific curiosity, a desire to utilize the energy dissipated, all describe man's reaction to the phenomenon of the tides. An anecdote holds that Euripides, unable to figure out the tidal phenomenon, committed suicide. Utilization of tidal energy goes back to classical tides, and thus the Byzantine general Belisarius put tide mills in the Tiber River during the siege of Rome, to get the power to grind grain. Floating mills functioned in the estuary of the Danube. But the forerunners of the electricity generating stations were numerous in areas of large tidal ranges: the south of the Iberian Peninsula, Normandy, Brittany, Wales, England. In the British Isles, centuries old mills kept at work as late as the Second World War.

Immigrants, Netherlanders, French, British, took into the Americas took the techniques with them and constructed mills in the United States, particularly on Long Island (New York), New England and Canada. A model of one such mill was reconstructed a short distance from the Annapolis-Royal pilot plant, Nova Scotia perhaps as a tribute to its ancestors.

Though tidal energy and harnessing its power retained the attention well before the 19th and 20th centuries, e.g. Mariano, Veranzio, Leonardo da Vinci, proposals were then formulated to capturing tidal energy and putting it to work in sophisticated schemes. Bernard Forest de Bélidor [5] focused attention in the *Traité d'Architecture Hydraulique* (1737), Decœur [6] proposed tapping the Seine River's tidal flow and deposited a patent (1890), Pein suggested a plant at Busum (Germany) (1912) [61], and Caquet and Dufour [7] deposited another patent in 1937.

3.1. Where is, or was, tidal energy harnessed?

When tidal power is mentioned one thinks immediately of the Atlantic coast of France where the only large tidal power station has been constructed and has been in operation for some 35 years. Brittany was the site of the first attempt of harnessing the energy of the tides, on the Aber Wrac'h, some 65 years ago. The undertaking ended in failure, due to lack of funds as the economic crisis of the thirties struck the World. It was that same crisis that motivated Franklin D. Roosevelt to launch his ambitious program of public works. Fascinated by the dissipation of tidal energy, he started the construction of a tidal power plant in the Passamaquoddy-Fundy area.

If that project was doomed as well, also due to lack of continued funding, it is the electricity lobby, particularly that of New England, that managed to torpedo the project, so as to safeguard its interests.

Quoddy and the Aber Wrac'h are not the sole projects that collapsed. The most commonly mentioned are those of Great Britain (England–Wales), which had eyed barrages on the Severn and Mersey rivers. Setting aside the consideration that, had a plant been constructed when first proposed it would have cost a fraction of the cost of such a venture today, one may think of the tons of petroleum that would have been saved since…1947! Across the Channel, perhaps the most ambitious scheme ever to be proposed, that of the Chausey Islands, has also been laid to rest, the success of the Rance River plant notwithstanding. (Fig. 1).

In other privileged sites plans were repeatedly afoot to construct tidal barrages. Among these closest to realization are those in Australia (e.g. in the Kimberleys), Argentina (e.g. San Jose Gulf, Valdez Project), Korea (near Garolim, Incheon Bay) and in the United States, on both coasts.

There were some short-lived plants. The one in Boston Harbor was a double-basin scheme but had to give way to the harbor expansion. In Iceland a plant using the tidal current had a brief existence. Another once functioned in Suriname. And several centrals in China came to a standstill due to sediment accumulation.

And precisely, speaking of China—it is the country that built the largest number of plants, with claims varying from 105 to perhaps as many as 130 [1] though mostly

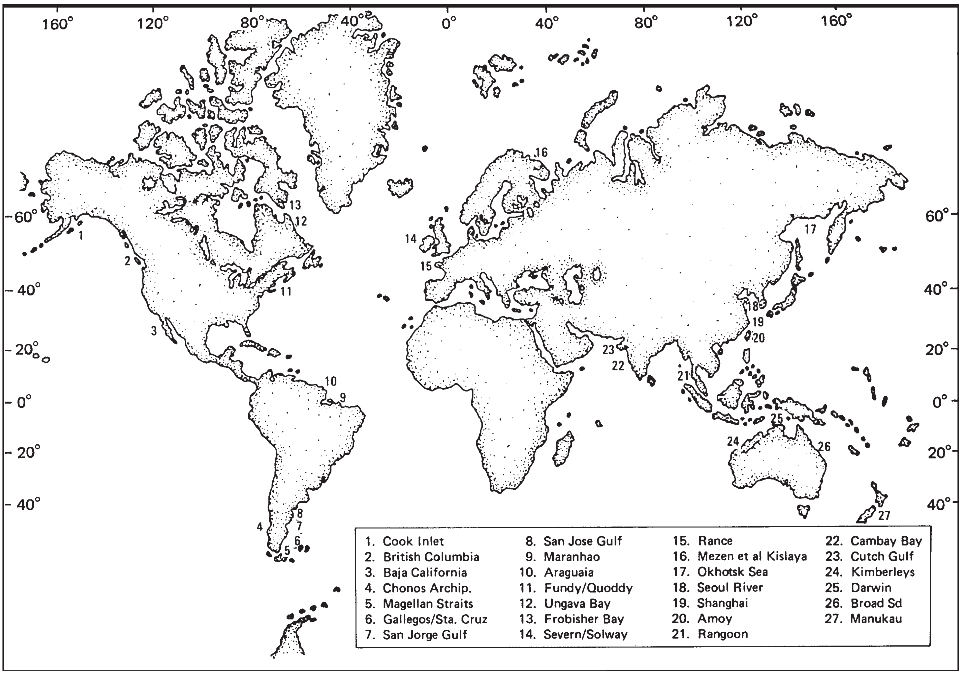

Fig. 1. Major tidal power potential plant sites: world distribution.

very small. But Canada and Russia each have a pilot plant. One is on Hog's Island in the Bay of Fundy, the largest reservoir of tidal power with the Sea of Okhotsk (Siberia), the other near Mezen (Russia). All these schemes tap tidal energy to transform it into electricity. Their forerunners are the tide mills which once dotted both sides of the Atlantic, and of the Channel, and even worked the tidal flow of the Tiber and the Danube (Charlier, 1998) [47]. These mills transformed tidal energy into mechanical power. They have fascinated men perhaps more since most of them became derelict, than when they were working, some as late as the mid 20th century. A few have been restored such as the Chatham Mill (Massachusetts), Ewing (near Southampton, England) and Plougastel (Brittany).

Japan conducted some studies 20 and 30 years ago, toying with the idea of building a plant in Ariake Bay (Kyu-Shiu). It would have required a rather long barrage (13.6 km 8.12 mi). Straflo turbines would have used the energy of a 4.56 m (15 ft) head. Even with side projects, electricity generated would have been too expensive.

If the 20th century tidal power plants are all based on the same concept, they differ in several aspects. The Rance scheme was constructed in the dry using expensive cofferdams and bulb-type turbines—allowing two-way generation—were installed. The Kislagubskaya scheme also uses bulb-turbines for power generation but cell-units, modules, were assembled on land, towed to the site and sunk there, thereby cutting costs considerably. Both the Rance and Kislaya plants' turbines are double-effect; the Canadian plant uses single-effect turbines. Annapolis-Royal was built on an island, required no cofferdams, and substituted Straflo turbines for the bulb-type ones. Little is known about the Chinese centrals except that they made use of existing dams and serve local communities or regions without any thought of being integrated into a Regional or National grid [1]. Had the Korean plant been built instead of derailing on the tricky path of international politics, it would most probably have been equipped with bulb turbines.

3.2. Dreams and realities

There are numerous sites around the world where tidal power could be harnessed. More have become potential locations with the development of low- and ultra-low head turbines (Fig. 2). Extensive studies have been conducted in prime areas: Argentina, Australia, England and Wales, Korea, Japan. Except for Wales, plans have been laid to rest: Argentina lacks the funds, Australia lacks sufficient customers, Korea is locked into a political furore with France, the potential builder. Japan had considered a Kyusyu-sited plant. Tides in Ariake Bay reach 4.56 m with a mean range of 3.18 m. The mean depth of water is 21 m and the maximum depth is 40 m. A barrage built to span the bay would be 13.6 km long. The output with 100 generators (compared with the Rance's 24) would be 500 MW. Annual electricity generated would be 68.4×10^{8} kWh. The price tag, in the seventies, for such a plant was estimated to exceed $2{,}5\times10^{10}$ Yen, around US$2500 million.

Few large plants became a reality (France, Russia, Canada); many small ones were built with modest means in China.

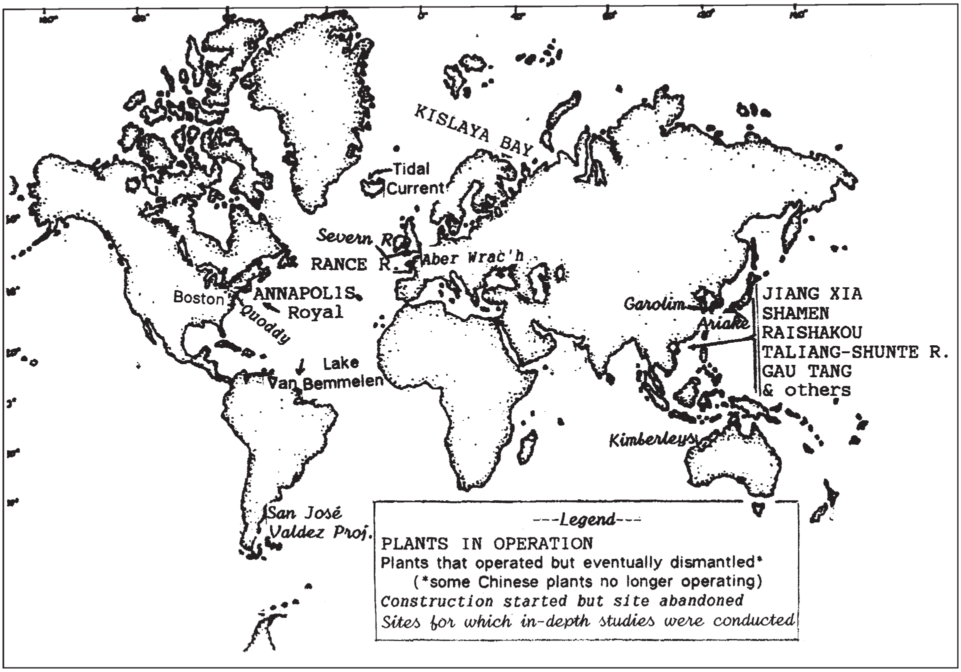

Fig. 2. Location of plants in operation or dismantled, or aborted and sites studied in-depth.

3.2.1. *The Rance River plant*

Located on the coast of Brittany the largest tidal power station includes a barrage—with fish pathway—that spans the Rance Estuary at about its narrowest site (750 m). A 14 m two-lane highway has been constructed atop the dam. Its approximate cost is a hundred million 1960-US$. Equipment ran 55% of cost and cofferdams 13%; the latter expenditure has been avoided in the construction of later plants. The semi-diurnal tides reach approximately 13.5–14 m. The plant operates on a combination double-effect and pumping scheme which provides for a production “tailored” to time of day and tidal amplitude, favoring the solar cycle. The maximum output is 240 MW and annual power generated is 544,000 kWh.

Inside the plant 24 bulb groups of 10,000 kW have been installed: bulb groups have reversible blades, allowing generation in both ebb and flood directions. Power is transmitted to Aube, Brest, Landerneau, Rennes and Paris. As long as the head remains a minimum 7 m the plant has, in a basin to sea direction, a capacity of 10 MW; it is much lower in the other direction. The purpose of the pumping function is to increase the head near high tide by storing water; near low tide pumping allows to over-empty the reservoir below sea-level. Pumping is not necessary for high tidal ranges (9 or 10 m).

In France obviously the dream came through.

3.2.2. The Kislaya Bay plant

Kislaya Bay (Kola Peninsula) is a White Sea inlet, near World War II famed Murmansk in the Russian Arctic. It is in the Arctic that most of Russia's tidal energy is dissipated. The dam was built by assembling on the site pre-fabricated sections between 40 m high cliffs. A narrow canal (40 m) establishes the communication with the sea. Materials adapted to the harsh climatic conditions were developed for use in construction (igneous rocks aggregates mix; epoxy resin insulation reinforced with glass-fabric). The canals depth is merely 3–5 m, a factor that has caused environmental problems [8,9].

Precast concrete cellular units were built on land, brought to the site and sunk into place by filling some cells with sand. The pilot plant uses the bulb type turbines also installed in the Rance River station.

Tides range from 9 to 13 m. At the plant the normal maximum is 11 m. The head is 15.2 m. The plant's capacity is 400 kW. The small bays of the country hold a power potential exceeding 3.2 billion kW (3.2×10^9 kW). It is far smaller than that on the Rance River measuring only 36×18 m with a height of 15 m. The site was also selected because of its vicinity to the existing power system. (Fig. 3).

Total electricity generated is estimated at 1800 kW.

3.2.3. Annapolis-Royal pilot plant

The Annapolis Royal plant, located on Hog's Island in the Bay of Fundy, in the middle of the intake canal supported by a vertical concrete pier on the lower Anna-

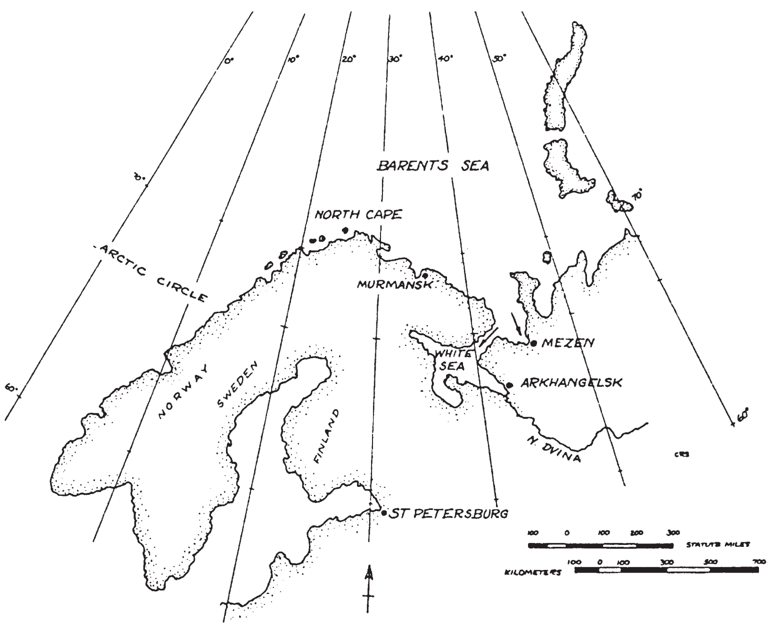

Fig. 3. Russian tidal power sites in Europe.

polis River, takes advantage of a 7 m tidal range. The plant's powerhouse is small (25×46.5×15.5m). It was built at a cost of 1982-C$46 million. A cofferdam was used.

It uses a single-effect Straflo turbine. Such turbine was developed in Switzerland in 1974 and is arranged in a horizontal water passage with the (rim type) generator field poles attached to a motor rim mounted around the periphery of the propeller; turbine and generator form a coupled unit without power shaft, saving thereby on powerhouse costs. Production is 50 million kW.

The dam is 225 m long. A fish pathway has been included, but apparently has not curbed mortality in a very significant manner (Dadswell and Rulifson, 1994) [35].

3.2.4. A hundred Chinese plants

According to the relevant Chinese literature, 128 plants would be in operation in China with a total capacity of 7638 kW. The largest plant, a multiple basin complex on the Shunte River, has a capacity of 304 kW. The same sources claim that the 40 kW Zhejiang Province plant (1959), predates the Rance Plant. Maximum heads range from 3.49–7.8 m, except for Jian Xia station where the head reaches 8.39 m; that plant and the Liu He Kuo one are double-effect schemes. (Fig. 4).

The possibilities of harnessing tidal energy and producing electricity in China were examined in 1958 (Anonymous, 1958) [10]. This work was a forerunner to the All Chinese Conference on Tidal Power held in Shanghai in 1959 (Anonymous 1959) [49]. Some tide mills operated in the southern regions of China centuries ago [1]. Tidal power development, focused on the gulfs of Fuchin, Shinhwang and Sanmen, and in 1978, at the Tokyo International Ocean Development Conference, China announced the construction of 80 or even 90 plants whose production would top 7000 kW. Further prospects were described in 1991 and reviews of operations were published in 1998 and 1999 [11–13,48]. Two plants, one at Taliang on the Shunte River, apparently use the double-effect scheme [1]. (Fig. 5).

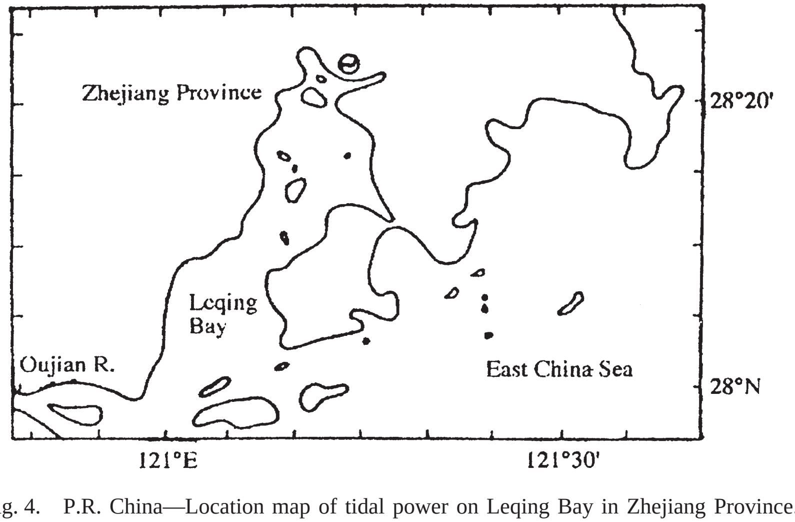

Fig. 4. P.R. China—Location map of tidal power on Leqing Bay in Zhejiang Province.

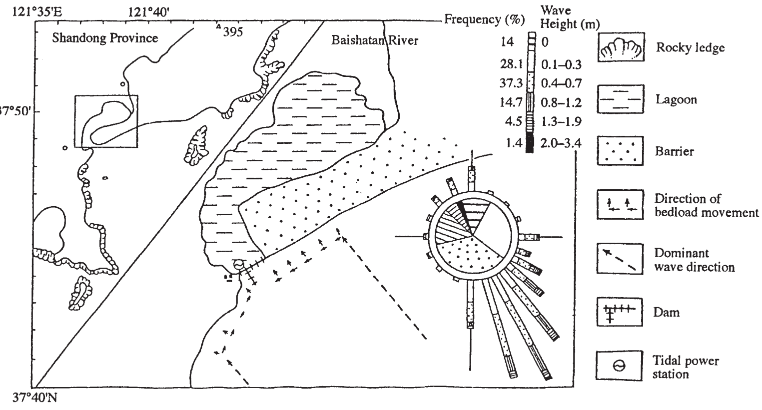

Fig. 5. The Raishakou tidal power station (P.R. China).

4. The plant

A tide mill consisted of a basin created by closing off a small bay with a dike, sluices allowing the basin to fill as the tide rolled in, and paddle-wheel that would turn as the basin was allowed to empty at ebb tide.

The tidal power plant consists of a barrage in which generators are lodged, sluices—sometimes a fish pathway, which however plays no role in power generation and is strictly an environmental device—turbines and a retaining pond. Occasionally several ponds (multi-basin plant) are involved. The link to the grid may also be considered as a plant component, although all plants are not connected to large grids. The plant can operate in different modes in function of timing of delivery, quantity and type of electricity required—maximum power or long duration.

4.1. The site

The choice of a site is subject to several factors. It may be deemed favorable to select an area close to large settlements or to established industries, Then again, it may be an impetus for development. In many sites sociological and economic conditions are quite favorable. The Rance River plant contributed greatly to the development of Brittany, until then a poor, thinly populated, agricultural area; it has been said that the plant pulled the region into the 20th century. Elsewhere, as in China, implantations of tidal power plants meant electrification. In Australia, Western Australia has large desert regions and the large quantities of electricity could not have been used in the Kimberleys, though the “economic panorama” has been changing. The cost of the real estate may, in some sites, be prohibitive; in Canada considerable money had to be paid to farmers dispossessed of their land.

Selection of a site is governed by other factors: would there be a conflict between existing economic activities and the construction of a plant? This was the determining factor as to why no tidal power station was even considered within the framework

of the gigantic Dutch Delta Plan: crustaceans' aquaculture. An argument militating as well in the Bay of Arcachon (France). And yet oyster culture has benefited from the Rance plant.

Rentability of the scheme will weigh, and the cost of the electricity produced will be all but determining.

Natural factors are extremely important: barrage construction is a costly undertaking, hence a narrow entrance to an embayment is a positive factor. The basin's characteristics and the quality of the soil underneath the barrage are to be excellent (Rouzé 1959) [55]. Indeed those characteristics will determine the complexity of building the barrage—the ratio of the aperture to the surface of the basin dimensions in absolute value, minimum depth, opening and more or less widening shape.

The geological nature of the area is important as increased sedimentation is a very serious menace to a plant. The slope of the resistance layer must be appropriate. Evidently, many of these considerations are as important for traditional hydroelectric barrages.

Even though new turbine designs have greatly reduced the need for considerable heads—the difference of elevation between the water in the retention basin and at sea-level—tidal range remains a factor to be carefully examined. The remoteness of electrical generation is less serious nowadays, due to the establishment of national grid systems and the use of high-voltage transmission lines.

4.2. Electricity generation

The simplest system is, of course, the single basin scheme. Here one-way, or ebb-and-flood operations are possible; in the latter instance, reversible blade turbines are needed. With ebb-and-flood operations with pump-turbines, generation of electricity is in both directions; during surplus periods it is pumped into storage reservoirs, with some of the power generated used for pumping. Simple turbines can provide high-head pumped storage; this permits continuous non-tide related maximum efficiency production.

Multiple basin schemes have been designed; only the dismantled Boston Harbor plant was built on that principle and some Chinese plants. Five alternatives exist: double-pool, which requires only simple turbines and can provide continuous production if the station is placed between the two basins; the Passamaquoddy central was conceived on such a plan. Pumping in both basins; pumping occurs during off-peak use periods to pump the high basin up, and the low basin down. Pumping is also possible in a pool-to-pool dam. In various types of tide-boosted pumped storage systems, basins of differing sizes located in different sites can be used; the tidal energy is utilized to increase the output of a de facto pumped-storage-type plant. (Fig. 6).

With tide-powered air-storage plants, tidal energy is used to directly drive air turbo-compressors. Compressed air is stored underground until called upon to drive gas turbines. In the tide-power hydrostatic-pump, a simple propeller turbine linked to the pump, converts tide-energy to a flow of high-pressure oil driving a Pelton

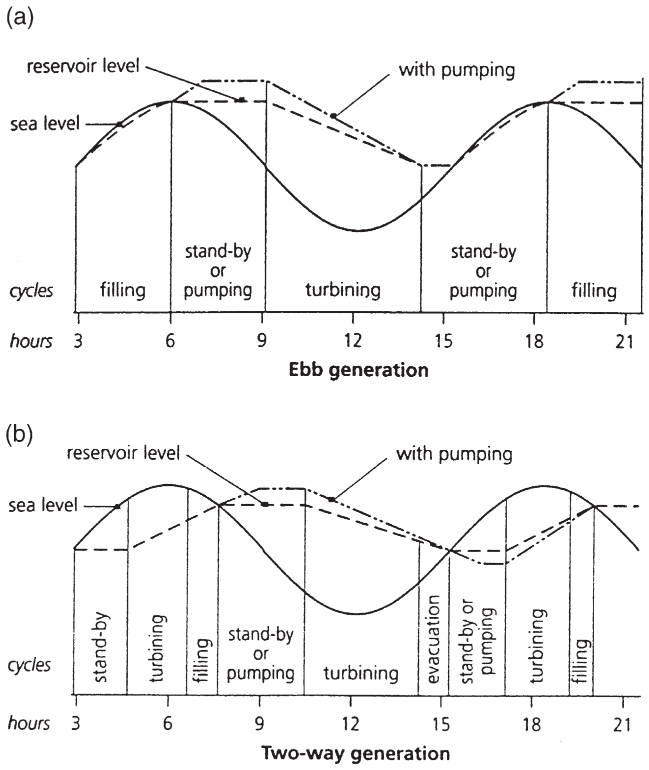

Fig. 6. Alternative operational modes at La Rance, France.

wheel coupled to an alternator. No electrical equipment is located in the marine environment.

In the case of the Rance River plant the bulb turbines allow generation at both flood and ebb tides while hardly any tide mill functioned in both current directions. However, there are in this scheme as many as six operation options: direct, viz. estuary to sea; reverse turbine operation (sea to estuary); direct (sea to estuary); reverse pumping (estuary to sea); and direct and reverse operation. All modes of operation do not yield the same results. It has thus been shown that the difference between single operation without pumping and such operation with pumping is about 10%, while double operation provides an increase of only 1%. Depending on the valuation method used, single operation without and with pumping provide a value difference of 10 to 30%.

Compared to single operation with pumping, double operation with pumping yields another 2 to 10% in terms of value (Hillairet & Weisrock 1986) [54]. The energy yield of pumping varies, depending on the modulation ratio, from 100 to 157%; the corresponding value can be considerable according to the restitution period.

During its lifetime, the Rance plant has been subject to several improvements:

convinced of the advantages of direct pumping, operators developed distributors and blades both fixed and adjustable, provided generators with a reinforced coreframe fastener system that allows synchronous start and improved access and maintenance conditions (Hillairet 1984) [53]. Instead of starting from standstill, pumping is preceded by operation as a sea to basin sluice, allowing the units to start at 30 to 40% of rated speed, prior to synchronization with the grid, thereby reducing generator stress.

4.3. Turbines

Though, as pointed out above, systems may function under some circumstances with simple turbines, schemes are usually envisioned with bulb, straflo or ultra-low-head turbines.

The bulb turbine is an olive-shaped steel shell containing a Kaplan turbine and an alternator. It acts as a turbine and pump. A bulb group—there are 24 units at the Rance River—is connected to a transformer linked by cable to a river bank sited substation. These turbines are well suited for low-ranges. The development of the bulb turbine was a determining factor in the construction of the Rance River plant.

An axial-flow turbine was designed as far back as 1919 by Leroy Harza and developed by the Swiss Escher–Wyss company. These turbines had rim generators. Straflo turbines— a modern version dating from 1974—are arranged in a horizontal water passage its field poles attached to a motor rim mounted around the periphery of the propeller, generally housed in a low-profile concrete powerhouse. The powerhouse costs are reduced because turbine and generator form a driving-shaft-less coupled unit.

Other low-head turbines which have been considered and occasionally estimated suitable are the Francis turbine, the Ossberger Cross-Flow [impulse] turbine, the Allis–Chambers tubular turbine, the Nohab turbines, the Neyrpic turbine and a Daniel Schneider designed turbine. These turbines can operate with heads of only 4 m and less, with the Schneider requiring about 1 m.

The wind power Darrieus turbines have recently been re-examined in Japan for use in tidal current power stations [14]. The characteristics of these turbines depend on the strength of rotor and number of blades. Studies recommend, however, that blocking of strait or bay be avoided [15].

Deviating from the traditional tidal power plant, a slightly different scheme was proposed for Taiwan [11]. It was suggested to generate power from buoyancy and weight at ebb tides. The system apparently can be used anywhere where there is a head, whether a coast, a dam or a pumped-storage reservoir. Perhaps a most significant feature is the ability to shift off-peak generation capacity to the peak need period. The shifting problem has been one of the contentious topics of tidal power generation.

As no barrage is needed, the plant requires less capital investment. A “removable barrage” scheme, which also involves re-timing, has also been designed by Gorlov [16,17]. He proposes to use compressed air to insure re-timing; electricity can be generated directly or compressed air can be stored for later power production. The usual dam is to be replaced by a thin plastic barrier hermetically anchored to the

bottom and bay sides. A cable stretched across the bay or inlet, attached to several floats, would support the plastic barrier and hold it above water level. Environmental impact would be benign, though a pool of stagnant water might be created behind the barrier; pulled to one side, the barrier would allow evacuation of the impounded water and even navigation.

4.4. Transmission and storage

A major problem with the utilization of tidal energy has been the difference between the occurrence of tides and the need for power. It has been a main argument of the opponents and skeptics. Considerable effort has been spent trying to solve the problem and several schemes have been proposed; these include the use of multiple basins in a scheme, compressed air systems, and more. Another reservation has been the problem of power transmission, but the development of high voltage lines has pretty well resolved it, as for instance in Brittany where the Rance plant has been hooked up into the French national grid. Transmission has become, in some cases, less expensive than coal transportation, making ocean-produced electricity competitive. For a 230 kW line as a unit of investment and transport capacity, a 500 kW line will cost 1.66 times as much but will provide six times the transport capacity, and a 8700 kW line costing 2 1/2 times as much will have a capacity 13 1/2 times greater.

Cables of 700 kW can carry current overland for a 2000 km distance. Capital investment costs drop with increased utilization, but exploitation expenses increase. Transmission losses decrease as tension increases and capacity increases several times faster than tension: 1000 MW for 400 kV, but 16,000 MW for 1500 kV. These figures are for alternating current; direct current transmission—such as between the north and south islands of New Zealand—is more economical if the distance involved exceeds 1000 km. Thought has been given to using cryocables, superconductors and vapor isolation.

Producing electricity for use at a later time can be realized by pumped storage; it is also conceivable by storing compressed gas in exhausted mineral deposit locations, also in aquifers' anticlines. Any gas can be stored in abandoned mines and even artificial cavities can be created for storage purposes. Gorlov's [18] scheme can be recalled in this regard. Hydrogen can be injected into salt deposits and stored at savings of 80, even 90%, over the cost of using surface positioned tanks. Use of hydrogen as an "intermediary" fuel is, however, not unanimously endorsed [19].

Finally, re-timing of tidal energy is possible with electrolytically produced hydrogen to be used as fuel when tide power and peak load demand differ. Hydrogen combustion can heat the air during peaks, and hydrogen can be produced during the off-periods using non-heated compressed air; the hydrogen does neither have to be stored nor transported.

Development of low-pressure air turbine technology, on an industrial scale, was urged already some time ago to strengthen hydro-pneumatic power plants' competitiveness (Baker and Wishart 1986; Cave and Evans 1986) [50,51].

4.5. Economics

The regularity from year to year of tidal power (less than 5% variation) is one of its main advantages. Co-lateral advantages are proper to a site: the dam can accommodate rail or road traffic, provide navigation improvements, cheap electricity, and a virtually inexhaustible supply of energy, it can constitute a send off for un- or poorly-exploited regions and is pollution free—though not entirely environmentally benign.

Though capital costs are high—but already reduced by one third by dispensing with cofferdams—the plant's useful life is two to three times longer than that of thermal or nuclear plants. Low-head water power could be converted to compressed air power, and smaller and cheaper high speed air turbo-generators would then produce electrical power. (Fig. 7).

As an example, for Bay of Fundy projects, the benefits of a tidal plant due to fuel cost savings would exceed by far capital and operating costs; the best ratio of benefit to cost was estimated, ten years ago at 2.6 or 3. Compared to alternate energy sources, the benefits to the market areas for tidal power were found similar to nuclear, and superior to coal. These market areas cover the (Canadian) Maritimes, New England and New York; Quebec, a natural customer for such power, will not become a patron because it has too much hydropower available. The Canadian Board that conducted the study on the basis of un-re-timed output of single effect plants concluded that tidal power is economically viable. The simulation was carried out for a period spanning 1995–2015 with generation, loads and prices assumed to remain stable beyond 2015. The role of tidal energy would be to reduce the amounts needed of the most expensive fuel consumed in the market area.

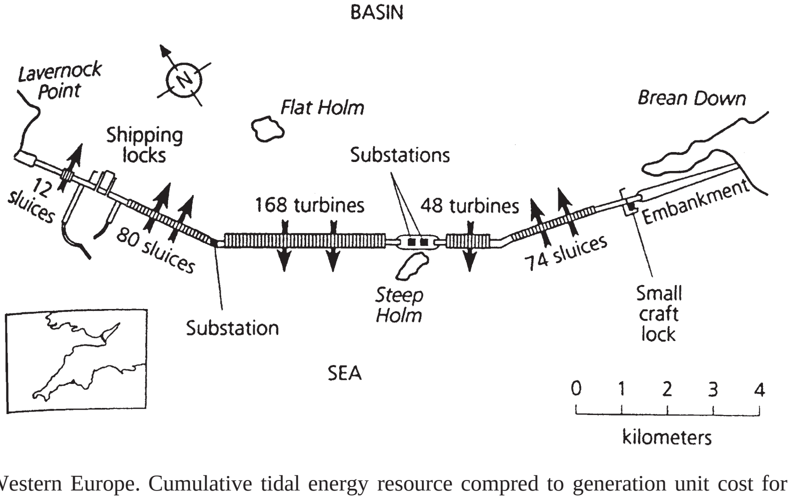

Fig. 7. Western Europe. Cumulative tidal energy resource compred to generation unit cost for a range of discount rates over a 120 years project lifetime. Calculated in 1990-US$. Note: some inaccuracies may exist since life-span of projects is rather estimated at 70 years. For the Severn barrage; with an estimated capital cost of US$/kW1,800, t a theoretical discount range of %/year, a kWH would cost 8 US¢.

Generation costs vary considerably from one country to another in function of a.o. social conditions; comparisons are thence all but meaningless. In Japan oil, gas and nuclear stations produce electricity at the lowest price, with coal costing slightly more; tidal power would cost three to four times more, making it, currently, unattractive. Critics of tidal electricity generation labeled the Canadian Annapolis-Royal "an expensive undertaking". Looked over in this estimation is the site of the plant, the huge compensation paid to farmers for their land and strikes that plagued construction.

The tidal power plant has no related fuel cost and thus, once capital cost is recovered, cheaper electricity becomes available, A break-even level is reached at the time a same age nuclear facility or thermal plant has to be replaced. The tidal power plant offers other "dividends" because, contrary to coal-fired plants, it is free from sulfur dioxide and carbon dioxide pollution, acid rain generation, water pollution, oil spills, waste products treatment, and decommissioning expenses.

4.6. Environmental effects

A tidal power plant does not spew fumes of smoke into the atmosphere, nor does it produce nuclear waste. If it unavoidably creates some environmental disturbances, it may be safely held that its impact is rather benign.

When nearly 40 years ago the Rance River plant got onto the drawing board the Quatrièmes Journées de l'Hydraulique were dedicated to the development of tidal power and the special issue of *La Houille Blanche* published a paper warning that the construction of a large number of tidal power stations could probably slow down the rotation of the earth. No such phenomenon has been thus far reported.

No environmental impact assessment, neither in depth or basic, was made before or during the construction of the Rance River tidal plant. This apparent "we don't care attitude" is to be attributed to the mentality of the times, and to the major concern that the plant's construction could perturb the entrance of vessels to the St Malo harbor. A local fish, the *lanson* (*lanzon*), disappeared due to habitat loss, but oyster culture was enhanced. Geologically speaking, the beach at St Suliac suffered serious damage, a situation partially redressed after the plant was completed; sandbanks disappeared, while high velocity currents were generated near sluices and powerhouses, and sudden surges may develop nearby. A reduction of tidal ranges has also been observed by 0.7 m from 13.5 m; on the other hand minima have increased.

From the economic point of view the impact has been "positive". The fishing industry has remained unaffected. Industry found its way to Brittany and surplus electrical power, through the hook-up with France's National Grid, is transmitted to other regions. The top of the dam is used as a two-lane 14 m wide highway, cutting off 35 km of the distance between St Malo and neighboring Dinard. A new community has sprouted: the Cité de la Gougeonnais has known a remarkable expansion. The plant did not damage tourism either, as it even opened new vistas of the river and, for many years, attracted visitors interested in the scientific achievement. Creeping up towards its 50th anniversary the Rance River central has satisfied its protagon-

ists. The bulb-turbines proved a good investment and they have been installed in dams around the world.

Neither was there an environment impact study conducted by the Soviets when they decided on the construction of the Kislaya tidal power plant near Murmansk. True, it is located in a forbidding environment, but, nevertheless, it must have some influence on the quality of water in the bay, and probably on the biology of the gulf.

No real assessment has been made of the potential effects of the implant of a major tidal power plant in the Bay of Fundy. Various academic studies ventured, however, the estimate that the tidal range would be reduced by 5% outside the Minas Basin and as much as 15 to 20% below the site. Sedimentation problems would be minor. The site of the Annapolis-Royal pilot plant, on Hog's Island, was seeded to minimize erosion. Shad might be influenced while clam production could be enhanced outside, but decrease inside the pool. Marshland drainage would be mildly unfavorably affected. On the other hand a plant's structure would act as a dike and provide protection against storm damage.

A thorough impact study—EIA and SIA—was made for the pilot plant, covering even protection and monitoring of marshes and agricultural lands, and headpond water quality. A fish-pathway was included in the project aimed at shad striped bass, salmon and gaspereaux. Erosion increase between Bridgetown and Annapolis-Royal is being closely watched.

A major tidal barrage will lead to stratification of the reservoir, while mixing seawards will be benign. A significant sedimentation increase is to be foreseen near-shore of the reservoir, but only a slight one outside the barrier. Re-suspension may be fostered by the filling and generating cycles of the operating central A good part of the existing intertidal zone may become permanently submerged.

Upwelling may increase, thereby favoring biological production. Habitat modifications will ensue, salinity will be reduced, and current speed lowered. Water exchanges may be reduced, while salt-water marshes would expand landwards. Some researchers concluded that instead of developing highly efficient systems, planners might rather think of extracting a small part of the energy from the total system.

While the site was attracting tourists prior to the construction of the tidal power station, interest has been substantially augmented. Economic benefits are noticeable from both the long- and short viewpoints.

If environmental and sociological impact studies have ever been conducted for a tidal power project, then it is for the Severn River (G.B.) barrage [20]. This is, of course, a case study, but it may serve as an example of what should be considered and examined. Shaw and his co-authors thus examined the water quality in the estuary, the effects of the construction and the operation upon wading birds, upon migratory fish, and on navigation to the major ports of the estuary. Yet, in this instance, the study discerned no insurmountable environmental impact, though recommended additional study (Heaps 1981) [52]. It foresaw that as the currents would become gentler fine sediments might accumulate. In the upper estuary pre-construction deposits might be redistributed, and rates of accretion increase. (Fig. 8).

Nowhere in the literature, whether in Chinese or English language texts, is there any mention made of an environmental impact study of the Chinese plants; local

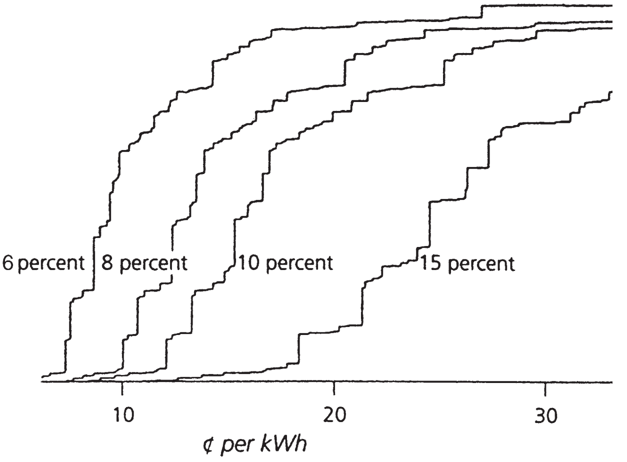

Fig. 8. Possible 8.6 GW Severn River Barrage (Great Britain). Schematic representation.

economics seems to have been the only concern. The absence of such study, particularly from a geological point of view, has cost dearly, since some plants ceased operation due to sedimentation. (Fig. 9).

Most sites suitable for the construction of a tidal power plant are also locales of complex ecosystems, among others wintering and migratory birds. Intertidal flats which they use as feeding grounds can be submerged by barrage-impounded water, and saltmarshes' flora may be lost. Assuming that land pollution sources impact

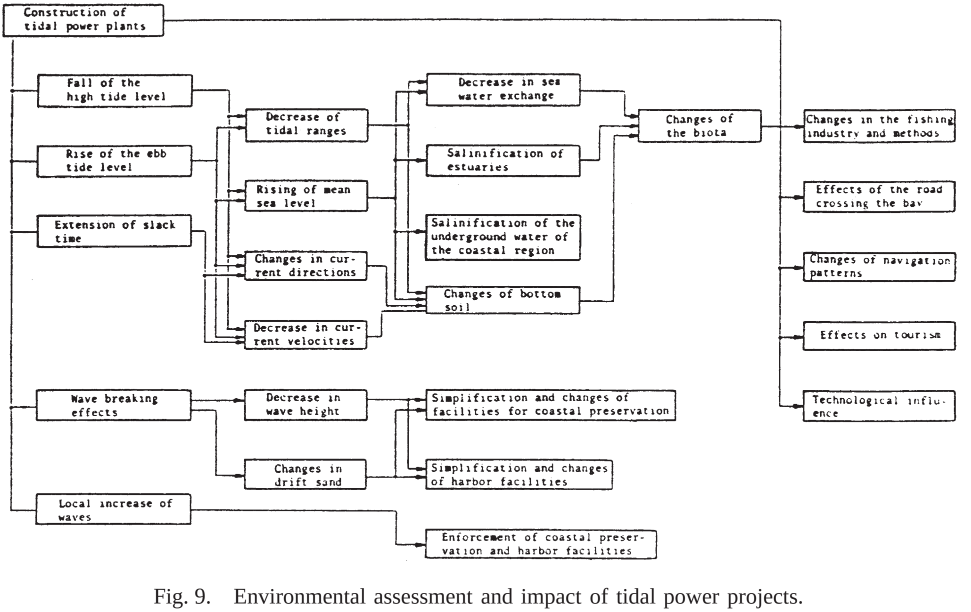

Fig. 9. Environmental assessment and impact of tidal power projects.

upon an estuary, the latter's impoundment may result in deterioration of water quality. Evidently effluent treatment before and after construction of the barrage may represent a non-entirely negligible additional cost, as tidal currents will be affected. Relief may however come through the presence of a larger mean volume of water [21].

Lesser impacts, more site-specific, are related to coastal protection, flood control and groundwater. As co-lateral uses are looked for so as to lower the capital investment, or provide immediate additional returns, tourism development may be considered but is not necessarily in harmony with nature conservation. (Fig. 9).

Assessments of environmental implications, ex post facto, have been numerous for the Rance River plants (e.g. [21,22]). At least 13 doctoral theses have been presented on the topic of environmental equilibrium in the area [23–32]. In fact the placing of cofferdams during construction, which cut the estuary, was the most damaging, a fact not reported in the Electricité de France's post facto assessments. Once in the operation stage things changed and an increasingly diverse fauna and flora colonized the area, showing a variable degree of biological adjustment; the ecosystems remain nevertheless strongly dependent on the operating conditions of the power station.

An environmental assessment was also conducted years after the Kisgalobskaia plant was constructed (1963–1968) and had operated for some 20 years. A first observation is that the water exchange between the bay and the open sea has been considerably reduced, salinity dropped in the upper 15 m of the water column, while hydrogen sulfide accumulated below that level.

Additionally to those chemical modifications, the pre-construction bio-ecosystem seems to have been totally destroyed. When in 1987 water exchange was brought up to 30–40%, it triggered a slow-paced restoration of the ecosystem; by 1992–1993 fauna and flora did not differ substantially in distribution in and out of the bay. The study conducted by Marfenin et al. [9] reveals that the construction of tidal power centrals may have impacts which are far from benign and that a pre-construction impact study is absolutely necessary, at least where small plants in narrow entrance bays are concerned. The difference in parasite fauna in cod and pollock were studied for Kislaya and Ura inlets near Murmansk [8]. Ecosystem research was further conducted by Semenov in 1997 [33]. It would be quite interesting, for comparison purposes, to have results of environmental studies—providing some were conducted—of small Chinese power plants.

Change in tidal amplitudes, phases spectral composition of sea-level oscillations, tidal currents' parameters are but a few of the modifications observed in the sea area around the power plant. These and other phenomena, such as suspended matter transport and movements of bottom sediments, can be estimated by modelling of tidal characteristics prior to tidal power plant implantation. Examples have been furnished for large plants which could be possibly constructed in the White and Okhotsk seas [34].

The inner Bay of Fundy's estuaries—like other large amplitude estuaries—are home to numerous migratory fishes, such as the endangered sturgeon, herring, shad, bass, salmon but also to squids, sharks, seals and whales. Studies have shown that

fishways at the Annapolis-Royal (Nova Scotia) power plant are not very effective in sparing marine life and mortality reaches, depending on such factors as species, size and turbine operation, 20 to even 80%. Were marine currents harnessed in the open ocean the impact of power stations may be such that a very serious decline in bio-populations could ensue. Dadswell and Rulifson's study [35] follows up earlier ones by G.L. Duffett (*Tidal Power* 1987 p. 101) and by W.E. Hogans on mortality of adult fishes (*American Scientist* 1985 and 1987) [56,57].

Never to be discouraged, opponents of a Fundy power plant raise the spectre of major ecological changes—besides fisheries losses—were a large station implanted in the upper reaches of the Bay. Variations in high (drop) and low tide (rise) sea level would compress the intertidal zone. New water levels for salt marshes would modify these habitats and modify primary production, which, however, would increase. Such changes would affect abundance of intertidal invertebrates, fish and migratory shore-birds [36].

Modelisation of water circulation in Passamaquoddy Bay has been attempted, with a model forced by tidal height variations at the oceanic boundary, fresh water run-off from rivers and parameterized fluxes of heat and momentum at the sea surface and sea bottom. The natural system shows strong tidal currents in channels and passes, but near zero residual flow in the bay itself. If the tidal flood is reduced in the modified system, a significant tidal-residual flow passes from Passamaquoddy into Cobscook bay; freezing at the surface is more common with a power plant, but mainly due to a lower heat flux from the bay bottom. It thus looks as if some environmental impacts which had been mentioned as deterrents for plant construction may well be less important than stated in the past [37,38]. Tidal residual currents have also been modelized recently for the Juan de Fuca Strait and the Southern Strait of Georgia [39].

5. Does the "C.E.O." get a pass?

This author asked ten years ago whether tidal power had come of age [40]; one may query whether, in general, does Conversion of the Energy from the Ocean get a pass? It is remarkable that the problem of tapping ocean energies remains resilient for so long. The matter bounces back periodically. Yet, positive action is limited.

Had there been such hesitation about railroads and aviation, where would we be ?

It took more than 150 years to finally decide to construct the Rance River plant; prior to this historic move of Charles de Gaulle, ailing tidemills were dying off, a timid tidal power plant had briefly functioned in Boston Harbor, another in Great Britain, still another in what is now Suriname and loudly heralded attempts on the US and French coasts aborted either for political reasons or struck down by the financial crisis.

In fact currently three stations are functioning, and well, in France, Nova Scotia and Russia. There is a growing literature about China's numerous mini-plants, but very little is actually known about them [1]. There is no shortage of announcements coming from China, Korea and Russia about, mostly large, new plants. But these

remain *pronunciamentos* at international congresses and in press releases, so far all *sans lendemain*. France shelved its mega-project of the Chausey Islands, but then the Electricité de France has been on a nuclear binge. Environmentalists raise the same fears of disturbed ecosystems, yet not so-environementally-benign river barrages are built. (Fig. 10).

The electricity production costs' calculations sometimes favor the tidal plant, or are said to be about the same as those of conventional or nuclear plants, while the conventional stations are CO_2-polluters. Capital costs remain high for a tidal power plant, but the longevity of the tidal plant is given at 75 years compared to 25 for a fossil fuel thermal central and between 30 and perhaps 40 years for a nuclear one.

No major new technologies are needed for the current construction of tidal power plants, however, it may pay off to foster development and research of the interface of a central's output with national grids, calculate a sound estimate of its economic interest, design and site proper implanting, and of course environmental effect and sustainability [41].

For countries which have large areas with great tidal amplitudes more voices are raised that favor alternative energy sources over the use of fossil products and nuclear

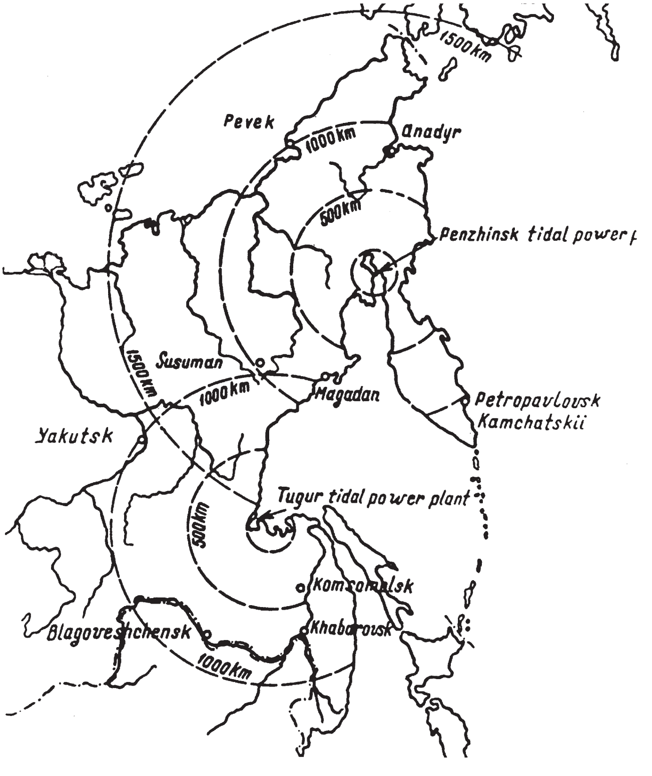

Fig. 10. Sketch map showing possible sites of large tidal power sites on the Sea of Okhotsk and zones of electrical power consumption (Russian Federation).

generation [42]. For Great Britain an article by Taylor [43] urged the development of nuclear and tidal power as a way to abide by the Kyoto Agreements and to formulate a national sustainable energy policy. And twice the Royal Society Parsons Memorial Lecture stressed the importance of tides' generated electricity [44,45]. Compact stations have been recommended [46].

Pleas to harness tides are more frequently and forcefully voiced than before. In this author's view, whatever the future of nuclear generation, and probably of thermal plants, tidal power, and other ocean sources ought to be added as at least complementary generators to quench man's thirst for kilowatts.

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